In situ Validation of the Source of Thin Layers Detected by NOAA Airborne Fish Lidar

Dr. Percy L. Donaghay
Dr. James Sullivan
Dr. Jan Rines
Graduate School of Oceanography
University of Rhode Island
Narragansett RI 02882
phone: (401) 874-6944 email: donaghay@gso.uri.edu
phone: (401) 874-6691 email: jrines@gso.uri.edu
phone: (401) 874-6142 email: jsully@gso.uri.edu

Award Number N000140811217

LONG-TERM GOALS

Our goal is to understand how physical-biological, biological-biological and chemical-biological interactions control the formation, maintenance and dissipation of thin layers of plankton and how the resulting thin layers impact *in situ* and remote sensing technologies of critical interest to the Navy. We are also interested in improving our ability not only to detect, characterize and map the temporal and spatial extent of thin layers, but also to improve our ability to predict their occurrence in a variety of ocean environments.

OBJECTIVES

Our short-term objective is to evaluate the relative importance of large non-spheroid phytoplankton and zooplankton in generating the thin optical backscattering layers detected by the NOAA airborne fish lidar in a variety of coastal and oceanic environments. We are particularly interested in determining the degree to which the cross polarization detector system (and other characteristics) of the airborne fish lidar make it sensitive to thin layers of large, non-spheroid phytoplankton and/or zooplankton, or other types of layered non-spheroid particulate material.

APPROACH

Our approach was to conduct field experiments in which we used a five-component strategy designed to minimize cost while maximizing the number of coincident airborne measurements of lidar backscatter and *in situ* measurements of inherent optical properties (IOP) and particle characteristics. First, we conducted these experiments in East Sound, WA, (a 2 by 12 km by 30 m deep fjord) where topography constrains lateral advection thus allowing airborne lidar and small boats to repeatedly sample the persistent thin layers of non-spheroid phytoplankton and zooplankton that frequently develop in this system. Second, we used multiple transects with the airborne lidar to create detailed maps of the spatial distribution of lidar backscattering layers throughout East Sound and adjacent waters. These maps were collected twice daily thus giving a highly detailed picture of temporal

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2010**	2. REPORT TYPE	3. DATES COVERED **00-00-2010 to 00-00-2010**

4. TITLE AND SUBTITLE **In situ Validation of the Source of Thin Layers Detected by NOAA Airborne Fish Lidar**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Rhode Island,Graduate School of Oceanography,Narragansett,RI,02882**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

changes in the spatial distribution of lidar scattering layers. Third, we transmitted these data to our small boat in real-time and used them to guide the selection of locations for collection of *in situ* measurements of fine-scale optical structure with our high-resolution profiler. Although most of these profiles were collected in locations where layers were detected by the lidar, we also collected them in areas where no lidar layers were detected. Fourth, we used these *in situ* optical profiles to guide the collection of discrete samples of plankton from features of interest for (a) immediate analysis of particle characteristics using video-microscopy and scanning flow cytometry on-board the sampling boat, and (b) post-cruise analysis of phytoplankton and zooplankton composition and abundance. Fifth, we increased the number of overlapping IOP profiles and information on particle characteristics by coordinating these cruises with several other ongoing projects in East Sound.

WORK COMPLETED

Analysis of May 2009 data: We have completed the processing and initial analysis of data from the 2009 experiment. We have shared the data with Churnside and worked closely with him in evaluating the correspondence between layers seen in lidar data and features observed in the IOP profiler, CytoSense flow cytometer and phytoplankton species abundance data. We have provided him with derived IOP products that he is using to calculate the impact of scattering and absorption on the intensity and vertical structure of layers detected by the co-polarized lidar detector. The results of these analyses have been presented at the 2009 Fall AGU meeting and at the 2010 Ocean Sciences meeting. Several papers are currently in preparation.

May 2010 East Sound cruise: We conducted our second cruise in May 2010. Each day during this cruise, we used multiple transects with Churnside's airborne lidar to create detailed maps (Figure 1) of the spatial distribution of lidar backscattering layers throughout East Sound and adjacent waters.

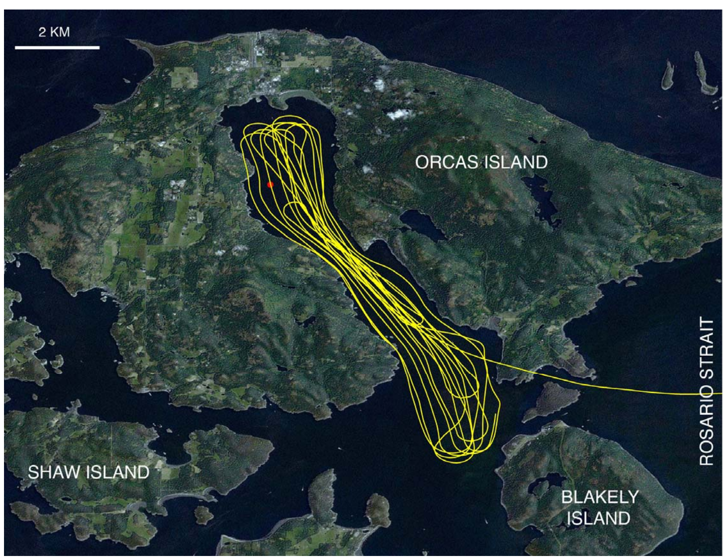

Figure 1. Example of typical airborne lidar flight track over East Sound and adjacent waters collected each morning and afternoon. The flight track (yellow line) is overlaid on a map of Orcas Island with the location of the ORCAS autonomous profiler indicated by the red dot.

We collected 299 transects in 2010 using 27 flights spread over a period of 14 days. With one exception, these flights were conducted twice daily thus giving a highly detailed picture of temporal

changes in the spatial distribution of lidar backscattering layers. We transmitted these data to our small boat in real-time and used them to guide the selection of locations (Figure 2) for collection of *in situ*

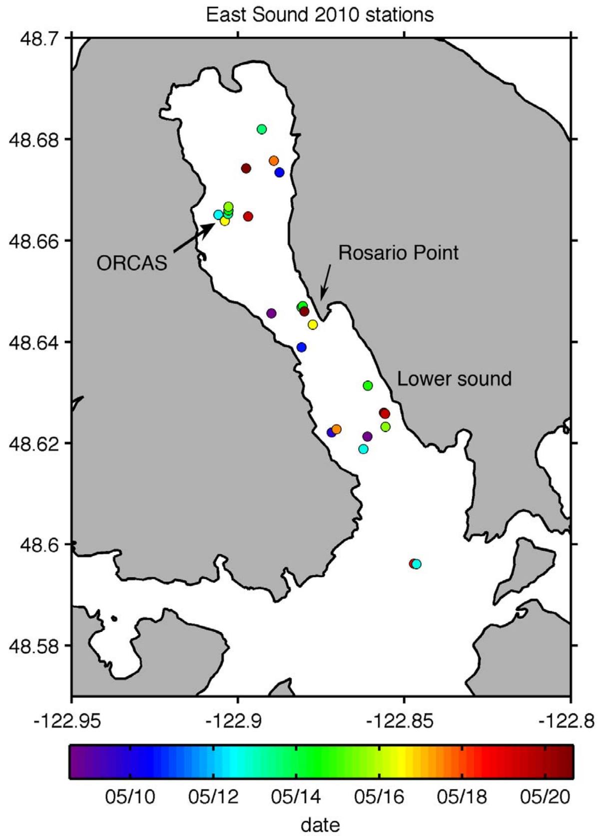

Figure 2: Location of profiles of fine-scale vertical physical and bio-optical structure collected using our high-resolution profiler in 2010. Samples for individual particle analysis using microscopy and scanning flow cytometry were collected at the profiler stations.

measurements of fine-scale optical structure. At each station we used our high-resolution profiler to collect replicate profiles of fine-scale vertical structure of (a) spectral absorption and attenuation by dissolved plus particulate material at 9 wavelengths (b) spectral absorption and attenuation by dissolved plus particulate material at 86 wavelengths, (c) spectral absorption of colored dissolved organic material at 9 wavelengths using a WET Labs ac-9 with 0.2 micron pre-filter, (d) optical backscatter at 3 angles, (e) spectral optical backscatter at 3 wavelengths and at 9 wavelengths, (g) chlorophyll-a fluorescence, (h) fluorescence of colored dissolved organic matter, (i) temperature, (j) salinity, (k) density, and (l) oxygen. We added a WET Labs ac-s absorption and attenuation meter and a WET Labs BB9 backscattering sensor to our high-resolution profiler this year to increase the spectral resolution of our absorption and scattering measurements while at the same time providing replicate measurements at wavelengths where the sensors overlapped. We used real-time analysis of these fine-scale profiles to select 67 features of interest from which we collected discrete samples for on-board analysis of individual particle characteristics using video microscopy and CytoSense scanning flow cytometry. We used the video microscope to characterize (a) the composition, size, morphology, and condition of the large phytoplankton and other types of large particles in each sample. We used CytoSense to measure the side scattering, forward scattering and spectral fluorescence (5 wavelengths) at 0.5 micron intervals along the length of each particle. We preserved sub-samples for later analysis in

the lab of phytoplankton composition and abundance. Samples for analysis of zooplankton size, abundance and composition were collected from features of interest using a pump and as integrated samples using a vertical net tow. These samples were preserved for analysis in the lab.

Analysis of May 2010 data: We have completed the initial processing and analysis of the high-resolution profiler data from the 2010 experiment. We have plotted the profiler data to look for thin layers and other features of interest. We have worked with Churnside to create a new approach that allows us to detect, map and quantify temporal and spatial variation in the depth, thickness, intensity and continuity of layers (thin or thick) measured by the cross-polarized detector on the NOAA fish lidar. This new approach involves (1) converting the raw lidar echograms into calibrated measurements of the cross-polarized volume backscatter coefficient measured at a scattering angle of π radians, (2) surface referencing the data, (3) applying a correction for attenuation, (4) determining the depth and intensity of the maximum in each profile, and then (5) calculating the normalized cross-polarized volume backscatter coefficient in each profile by dividing the intensity values at each depth by the intensity at the maximum. We have worked closely with Churnside in using these data to evaluate the temporal and spatial variation in lidar backscatter and the correspondence between layers seen in the lidar data and features observed in the IOP profiler data. We have conducted a preliminary analysis of the microscopy and CytoSense scanning flow cytometry data to assess temporal changes in the abundance and characteristics of the large phytoplankton and other particulate material. We have used this preliminary analysis to help interpret changes observed in the lidar and *in situ* optical profiler data.

RESULTS

Several lines of evidence indicate that layers of large, non-spheroid phytoplankton were responsible for most of the cross-polarized lidar backscattering layers seen during the second half of the 2010 cruise. First, phytoplankton samples collected from inside the lidar backscattering layers were dominated by the type of highly diverse community of large, non-spheroid diatoms (Figure 3) hypothesized to alter

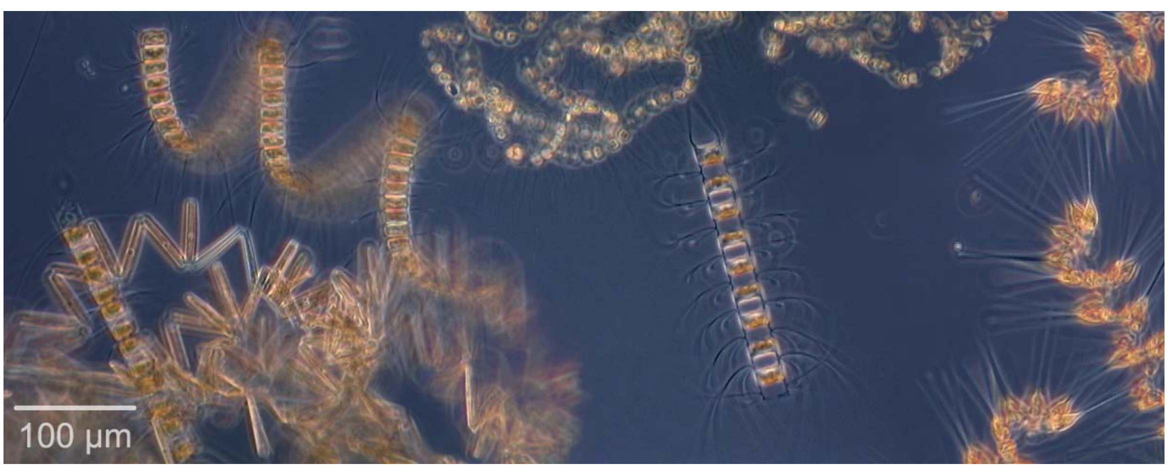

Figure 3: Photomicrograph of the phytoplankton community during the May 2010 cruise. The figure shows that the phytoplankton community was dominated by a highly diverse bloom of non-spheroid diatoms that formed large (up to 1 millimeter long) colonies that varied in shape from long and linear to spirals and large globular forms. The spiny diatoms of the genus Chaetoceros were especially well represented with > 20 species.

the polarization of lidar backscatter (Churnside and Donaghay, 2009). Although the abundance and diversity of this community declined toward the end of the cruise, our initial analyses indicate that some of these large non-spheroid species remained sufficiently abundant to dominate chlorophyll layers until after a storm that started late on May 19, 2010. Second, the vertical structure of the optical layers detected by the cross-polarized lidar detector was quite similar to vertical structure of absorption at 440 nm by phytoplankton chlorophyll a (compare Figure 4a and b), but differed above and below the layer from high-resolution profiler measurements of scattering and backscattering (compare Figure 4a

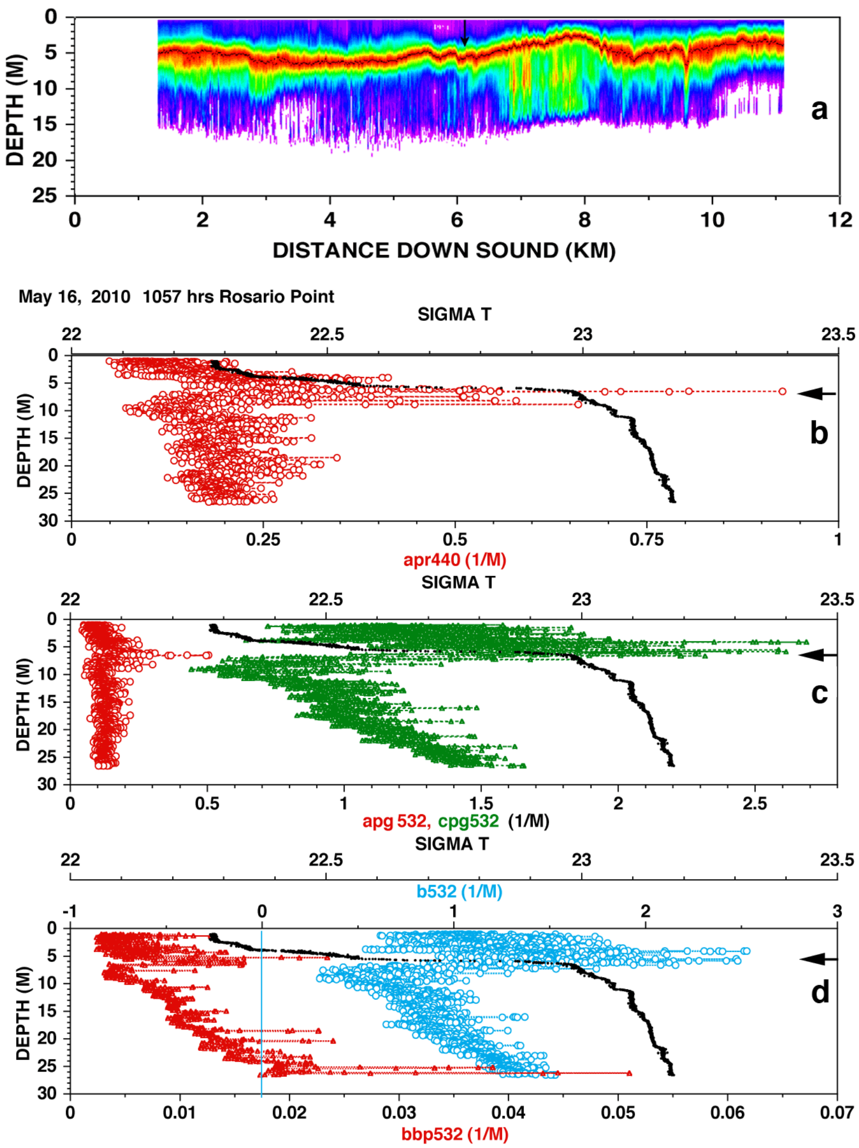

Figure 4. Comparison of the vertical structure of the normalized cross-polarized volume backscatter coefficient (at a scattering angle of π radians) measured by the NOAA airborne fish lidar at 1020 hours on May 16, 2009 (a) and the corresponding variation at a nearby location (vertical arrow in 4a) in fine-scale vertical structure of density (black dots, 4b, c, d), absorption by particulate material at 440 nm (the peak in absorption of chlorophyll) (red circles, 4b), absorption by dissolved plus particulate material at 532 nm (red circles, 4c), attenuation by dissolved plus particulate material at 532 nm (green triangles, 4c), scattering at 532 nm (cyan circles, 4d), and backscattering at 532 nm (red triangles, 4d). The arrows in 4b, c and d at 6 m indicate the depth of the lidar backscattering layer at the location where we collected the in situ optical profile. The figure shows that while the cross-polarized backscattering layer at 6 m) detected by the lidar corresponded with the depth of the primary layer detected by the absorption and scattering sensors on the high-resolution IOP profiler (4b, c, d), the vertical structure of lidar backscatter is similar to that of chlorophyll absorption at 440 nm (4b) in that both have minima in surface waters, but quite different from optical scattering measured by the ac-9 and backscattering sensors (4d) that have intermediate values in surface waters and a minima below the peak.

and c). This is consistent with the our hypothesis that while the large, chlorophyll-rich non-spheroid phytoplankton dominated the cross-polarized lidar backscattering and possibly the bulk backscattering at the depth of the chlorophyll layer, bulk scattering outside the layer was dominated by other types of particles that had little chlorophyll and little impact on the polarization of the lidar backscatter. Third, spatial variation in the vertical structure (Figure 5a) and the intensity (Figure 5b) of cross-polarized

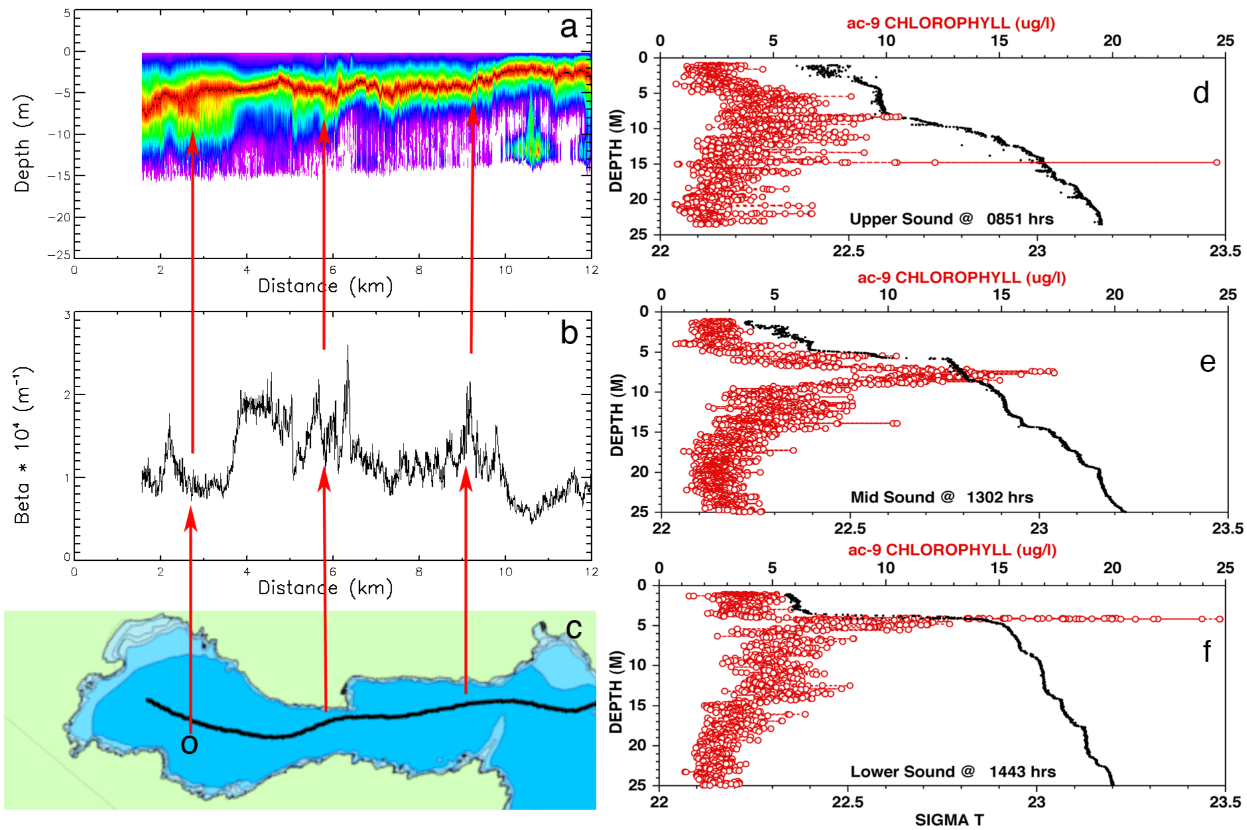

Figure 5. Comparison of the variation in vertical structure of the normalized cross-polarized lidar volume backscatter coefficient (5a) and the peak intensity of the cross-polarized lidar volume backscatter coefficient (Beta, 5b) measured on May 14, 2010 by airborne lidar at 1433 hours and the corresponding variation in fine-scale vertical structure of density (black dots, 5c, d, e) and chlorophyll) (red circles, 5d, e, f) measured with the high-resolution profiler in the lower sound at 1443 hours (5f), the middle sound at 1302 hours (5d), and the upper sound at 0851 hours (5d). The figure shows a striking similarity in the width, intensity and depth of the vertical lidar and chlorophyll a profiles.

lidar backscattering layers was highly correlated with changes in the intensity and shape of the chlorophyll layers measured by the high-resolution profiler at selected locations along the axis of East Sound (Figures 5d, e, f). As illustrated in Figure 5, this was true regardless of whether the lidar backscattering and chlorophyll layers were thick (as in the upper sound, Figure 5a, d) or thin (as in the middle and lower sound, Figure 5a, e, f). This should not be surprising since discrete samples revealed that the chlorophyll layers in all three cases (Figure 5d, e, f) were dominated by large non-spheroid

phytoplankton hypothesized to be the source of the cross-polarized backscattering layers. Fourth, temporal variation in the vertical structure (compare Figure 5a and 6a) and the intensity

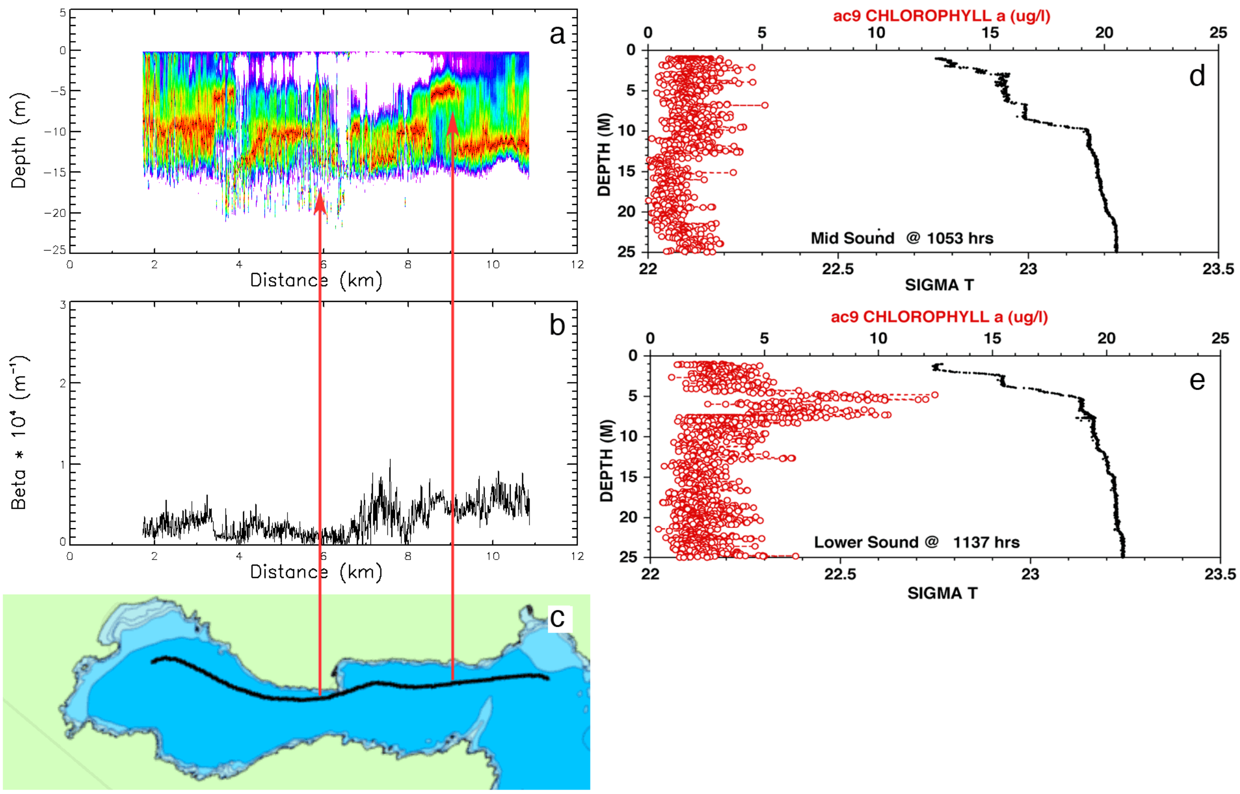

Figure 6. Comparison of the variation in vertical structure of the normalized cross-polarized lidar volume backscatter coefficient (5a) and the peak intensity of the cross-polarized lidar volume backscatter coefficient (Beta, 5b) on May 19, 2010 measured by airborne lidar at 0930 hours and the corresponding variation in fine-scale vertical structure of density (black dots, 5c, d, e) and chlorophyll a (red circles, 5d, e) measured with the high-resolution profiler in the middle sound at 1053 hours (5d) and the lower sound at 1137 hours (5e). The figure shows a striking similarity in the width, intensity and depth of the vertical lidar and chlorophyll a profiles.

(compare Figure 5b and 6b) of cross-polarized lidar backscattering layers was highly correlated with changes in the intensity and shape of the chlorophyll layers measured by the high-resolution profiler at selected locations along the axis of East Sound (compare Figures 5e and f with 6d and e). This effect became particularly apparent near the end of the cruise when dramatic declines in the diversity and abundance of large, non-spheroid diatoms were correlated with the disappearance of chlorophyll layers (Figure 6d) and cross-polarized lidar backscattering layers (left arrow, Figure 6a) in the region near the middle of the sound and declines in intensity of the few thin cross-polarized backscattering layers (compare Figure 6b to 5b) and chlorophyll layers (compare Figure 6e to 5f) that were detected in lower East Sound.

IMPACT/APPLICATION

This project has several important impacts/applications. First, the excellent agreement between the patterns of occurrence of thin layers detected by airborne lidar and the layers of large diatoms detected *in situ* by our optical profilers strongly supports the hypothesis that backscattering by thin layers of large non-spheroid phytoplankton can be sufficiently intense to be detected by airborne lidar. This is a huge breakthrough not only because it provides the first evidence that the layers observed by Churnside and Donaghay (2009) in coastal and open ocean regions could be the result of layers of non-spheroid phytoplankton, but also because it provides an approach that can be used to evaluate the extent to which this is true for other types of non-spheroid phytoplankton and zooplankton. Second, our initial analyses suggest that we can use the existing data set to map the spatial extent and temporal evolution of thin and thick phytoplankton layers during the development and collapse of the multi-species bloom of large, non-spheroid phytoplankton that occurred in East Sound during our 2010 cruise. This represents a major breakthrough that not only allows us to put our *in situ* measurements of fine-scale optical and biological structures and characteristics in a broader context of patch continuity, but also opens the possibility of using the sequential airborne lidar maps we collected to track and quantify the lateral advection of thin layers as they were modified by physical and biological processes. As pointed out by Donaghay and Osborn (1997), such a capability is absolutely essential to testing existing thin layer models and developing improved numerical models that can better predict their occurrence and dynamics in a variety of ocean environments. Equally importantly, it opens the possibility of using sequential airborne lidar maps to detect and track patches and thereby guide *in situ* sampling by ships and other mobile platforms. This could revolutionize the way we study subsurface layers in much the same way that ocean color satellites have revolutionized the way we study phenomena with surface chlorophyll signatures. Finally, the large number of coincident measurements of fine-scale optical structure and the intensity of co- and cross-polarized lidar returns provides a rich data base that could be used to increase our understanding of how to maximize the penetration depth and particle characterization performance of the lidar systems that the Navy requires to meet their research and operational needs.

RELATED PROJECTS

This project has been coordinated with two closely related projects. First, we have coordinated our efforts with those of James Churnside who has been funded through a companion ONR contract N00014091P20039 for his component of the project. Second we have coordinated this project with our ONR Grant N000140910492 entitled *" In situ* quantification of the impact of episodic enhanced turbulent events on large phytoplankton". The PI on that grant is Percy L. Donaghay with Jan Rines and James Sullivan as co-PIs. This project has also been coordinated with our NOPP holocamera project entitled " A submersible holographic camera for the undisturbed characterization of optically relevant particles in water (HOLOCAM)". This project was funded with James Sullivan at WET Labs as the lead PI, with subcontracts to Percy Donaghay (PI, URI subcontract) and Joseph Katz (PI, JHU subcontract). We also coordinated our efforts with Alan Weidemann who used gliders and a ScanFish profiler to map spatial changes in fine-scale physical and bio-optical structure. In addition, Weidemann measured fine-scale optical and physical structure at selected locations using a high-resolution bio-optical profiler. This coordination with Weidemann's NRL supported project allowed us minimize our mapping efforts, thus allowing us to focus on evaluating the *in situ* source of lidar backscattering.

REFERENCES

Churnside, J.H. and P.L. Donaghay, 2009. "Spatial characteristics of thin scattering layers observed by airborne LIDAR," ICES Journal of Marine Science 66: 778-789. Advanced Access publication February 25, 2009, doi:10.1093/icesjms/fsp029.

Donaghay, P.L., Osborn, T.R., 1997. Toward a theory of biological-physical control of harmful algal bloom population dynamics and impacts. Limnology and Oceanography 42(5), 1283-1296.